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Comparison of local equivalent temperatures and subjective thermal comfort ratings with regard to passenger comfort in a train compartment

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Abstract. Two methods for assessing thermal passenger comfort are analysed and compared to each other in terms of different ventilation concepts and different inflow air temperatures in a generic train laboratory. The studied ventilation systems comprise state-of-the-art micro-jet ventilation and a novel vertical ventilation system called displacement ventilation. The latter is based on a homogeneous and low-momentum air supply near the floor. In a first step, tests with human subjects are conducted addressing both temperature sensation and evaluation. In a second step, objective thermal comfort parameters are acquired using a calibrated thermal manikin, which enables the measurement of local equivalent temperatures. For reason of comparability, the results of the subjects test are converted into equivalent temperatures. The results prove that both methods, subjective and objective, correspond well under steady-state thermal conditions. The data of the subject tests are characterized by significantly higher variations compared to the experimentally determined values. Concerning the overall thermal comfort, both ventilation systems show comparable results for the two investigated inflow air temperatures. However, the comfort distribution over the body parts differs significantly between the two ventilation concepts.

1. Introduction

In its 2011 white paper on transport [1], the EU defines the goal to achieve a '50 % shift in middle distance passenger … journeys from road to other modes' by 2050. The main motivation for this challenging goal is 'to achieve a 60% reduction in CO_2 emissions and a comparable reduction in oil dependency'. For a realistic chance to shift the passengers to trains, the attractiveness of this transport mode has to be increased. Therefore, the EU defines passenger thermal comfort as one of the main characteristics of service quality to be enhanced. Especially for long-distance traffic, thermal comfort is besides many other aspects like seating comfort and noise one of the key parameters for people's well-being. According to [2], thermal comfort is defined as 'that condition of mind that expresses satisfaction with the thermal environment'. Physically, thermal comfort cannot be captured as a single measurement quantity. It is rather an integral quantity including the air temperature, air velocity, mean radiant temperature, relative humidity, metabolic rate and clothing insulation. Nevertheless, recent, well-calibrated measurement systems, e.g. the dressman [3] or DLR manikins [4], are capable of capturing the equivalent temperature, which is an accepted quantity for the evaluation of thermal comfort [5]. Furthermore, the reduction of total energy demand per train journey is an important issue. The HVAC system of modern long-distance trains is responsible for 20-30% of the train's total energy consumption. Accordingly, the implementation of new, energy-efficient ventilation systems is a key factor for the reduction of CO_2 emissions. Previous investigations [6] have proven that novel concepts like cabin displacement ventilation provide a 40% higher heat removal efficiency compared to state-of-the-art ventilation concepts like micro-jet ventilation, which are mainly designed to meet the requirements defined in the standards [7]. However, a disadvantage of the cabin displacement ventilation is a strong vertical temperature gradient resulting in the lower body parts being too cold [8].

The aims of the present study are twofold: Firstly, we want to compare the subjective rating and the measured local thermal comfort index using a calibrated DLR manikin for different ventilation concepts and different mean temperatures of the compartment. Secondly, the different ventilation concepts, namely state-of-the-art micro-jet ventilation and cabin displacement ventilation, will be evaluated regarding the thermal comfort.

2. Experimental setup

2.1. Generic train laboratory

Within the framework of the next generation train (NGT) project, a full-scale generic train laboratory with a realistic geometry was set up at the DLR in Göttingen in order to investigate different ventilation concepts in terms of thermal comfort, ventilation performance and energy efficiency. The lower deck of the double-deck high-speed train is equipped with 24 real train seats separated in six rows, see figure 1a. The cabin's dimensions are 6.13 m length, 2.88 m width and 1.95 m height. For air conditioning, an HVAC system is used providing inflow air temperatures between 10°C and 50°C at volume flow rates up to 300 l/s (with 10 l/s accuracy). Figure 1b shows the thermal manikins (TM) seated in the laboratory during the experimental studies addressing the objective evaluation of the thermal comfort. These TMs are used to simulate the sensible heat emission and obstruction of real passengers. In the present study, each TM was operated at a constant heat release of 75 W.

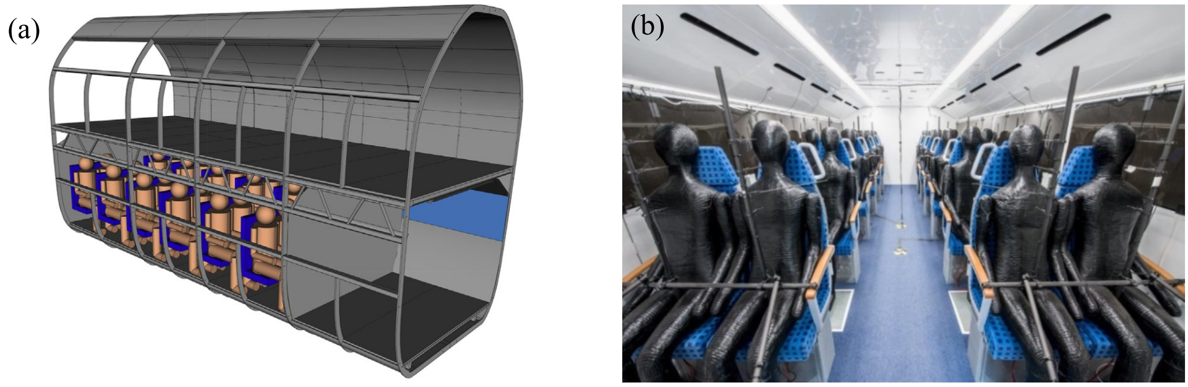

Figure 1. (a) CAD sketch of the generic train laboratory. (b) Image of TMs seated in the laboratory. Images © DLR.

In total, more than 180 resistance temperature probes with an accuracy of $\pm 0.2K$ were installed in order to acquire local surface and fluid temperatures (e.g. at the inner and outer sidewalls, in all air in- and outlets) as well as to record the temperatures at comfort-relevant positions as described in [7]. More detailed information about the laboratory and the used measurement techniques is given in [6].

2.2. Investigated ventilation concepts

The present study compares the objective and subjective assessment of thermal comfort for two different ventilation scenarios. As indicated in figure 2a, a simplified state-of-the-art ventilation system based on an air supply through micro-jet nozzles (micro-jet ventilation - MJV) was embedded in the aisle at ceiling level. Here, the air enters the cabin via numerous jets with rather high momentum. Thus, MJV leads to a high degree of mixing of the incoming fresh air and the recirculated cabin air resulting in a homogeneous temperature distribution. The air leaves the compartment through lateral outlets at ceiling level.

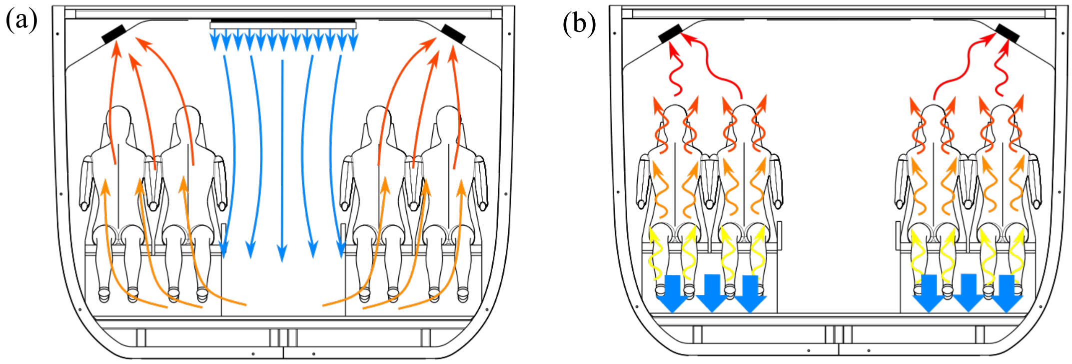

Figure 2. (a)Sketch of MJV with air supply through micro-jet nozzles at the ceiling. (b) Illustration of DV with low-momentum air outlets under the seats.

Likewise, a novel ventilation concept, called floor-based displacement ventilation (DV), was studied in detail This concept is defined by a very homogeneous and low-momentum fresh air supply at floor level, see figure 2b. For this system, air distribution bags made of a very dense membrane were mounted under the seats. The incoming air generates a lake of fresh air near the floor of the compartment. In the vicinity of the heat loads (e.g. passengers or TM), the air temperature increases and air rises due to the buoyancy. Finally, the warm air leaves the compartment through slit-shape outlets in the lateral parts of the ceiling. Consequently, the airflow within the cabin is purely dominated by thermal convection in this ventilation scenario. One advantage over the first concept is that comfort-critical draughts are less likely to occur due to the very low inflow velocities. However, early studies regarding pure displacement ventilation [6] revealed temperature stratifications from ankle to head level of up to 7 K.

3. Methodology

3.1. Subject tests

For the subject tests, the compartment was occupied by 20 participants (see figure 3a) for each scenario, who had been briefed in advance to wear standardized clothes with long sleeves, trousers and no boots or scarfs, which represents a clothing insulation of approximately 0.8 clo. In the seats of the first row, four TMs were positioned, each surrounded by six temperature probes at different heights in accordance with [7]. For each test, the experimental procedure comprised the investigation of two different temperature scenarios with half an hour of settling time in between. These 30 minutes are enough to decrease the inlet temperature by 2 K. However, this time slot is too short to reach an equilibrium temperature of the interior and inner lining due to their thermal inertia. A detailed description of the procedure including a sketch of the time-line can be found in [6]. Using specified questionnaires, the subject’s climate assessments was conducted at the end of each scenario. Besides many other parameters, the subjects rated the perceived intensity of the ambient temperature on a scale of 1 (very cold) to 7 (very hot) [8]. In the present study, only this evaluation parameter was used for comparison of subjective and objective thermal comfort ratings.

3.2. Equivalent temperature

In addition to using thermal manikins as heat loads and obstruction, they were also used to evaluate thermal comfort based on the acquisition of local equivalent temperatures. According to [9], a TM was calibrated at a constant heat release of 75 W in a dedicated temperature-controlled box providing isothermal conditions. The boundary conditions (i.e. fluid and surface temperatures) within the box were monitored by 25 temperature detectors. Additionally, the averaged surface temperatures ($\overline{T_S}$) of selected body parts were recorded using a high-definition infrared (IR) camera. Consequently, the dependency of the segmented surface temperatures of the manikin and the mean ambient temperature within the box, which is also the equivalent temperature in this controlled environment, was fitted using a linear regression. Detailed information about the calibration process is given in [4].

In the present study, the calibrated manikin was placed at seating position C02, see figure 3b. The IR camera was installed on top of the backrest of seat position C01. Hence, the optical accessibility for the whole TM's body was ensured. Using the appraisal (for summer conditions) of the thermal comfort based on [9], the corresponding T_{eq} values were rated on a scale of 1 to 5, ranging from too cold (1) via neutral (3) to too warm (5).

(a) (b)

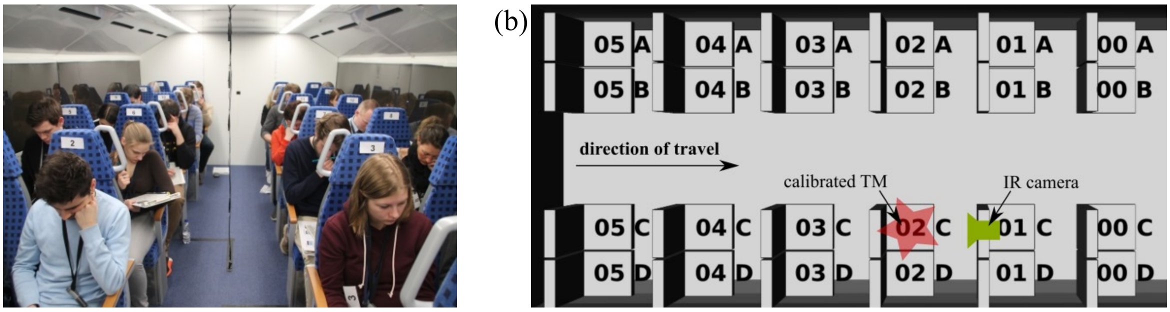

Figure 3. a) Image of the laboratory equipped with subjects. b) Seating plan with the position of the calibrated TM and the IR camera. Images © DLR.

3.3. Experimental procedure

Two different ventilation scenarios were studied, each with two different air supply temperatures (T_{in}), in subject tests and for the experimental acquisition of T_{eq} values. In total, eight different cases (Cs1 to Cs8) are investigated and summarized in table 1. Here, the mean temperature within the passenger compartment (T_{im}) was calculated in accordance with [7].

Table 1. List of examined ventilation scenarios.

	Cs1	*Cs2*	*Cs3*	*Cs4*	*Cs5*	*Cs6*	*Cs7*	*Cs 8*
Ventilation	MJV	MJV	MJV	MJV	DV	DV	DV	DV
Study with	manikin	subjects	manikin	subjects	manikin	subjects	manikin	subjects
T_{in}	15°C		19°C		15°C		19°C	
T_{im}	≈ 21.8°C		≈ 25,8°C		≈ 19.9°C		≈ 23.9°C	

For all investigated cases, the temperature set value of the inflowing air (T_{in}) was maintained with a maximum deviation of less than 2%. During all studies, the total volume flow rate amounted to $\dot{V}$=230 l/s.

4. Results and discussion

In order to compare the different ratings, the subjective assessment of the temperature sensation captured on a seven-point scale was translated into the five-point scale of the evaluation criteria given in [9] using the following equation: $S_{Teq} = (S_{Sbj} + 0.5)/1.5$. Here, S_{Teq} represents the scale of the equivalent temperature and S_{sbj} denotes the seven-point scale of the subject questionnaires. Based on the linear correlation between the five-point scale and the corresponding equivalent temperature values, the translated results of the subject tests were additionally converted into equivalent temperatures. As described in section 3.2, the thermal comfort rating based on the acquisition of local T_{eq} values was conducted at seat C02 solely. To improve the statistical significance, the averaged subjective comfort ratings of all aisle seats were taken into account for the comparison. To avoid systematic averaging errors due to the different thermal conditions on both body halves, i.e. the side on the aisle might feel different compared to the side next to the seat neighbour, the averaging took this mirror symmetry into consideration. Figures 4 and 5 show the resulting comparison between these two methods of comfort analysis for the MJV scenario and for the DV ventilation system, respectively.

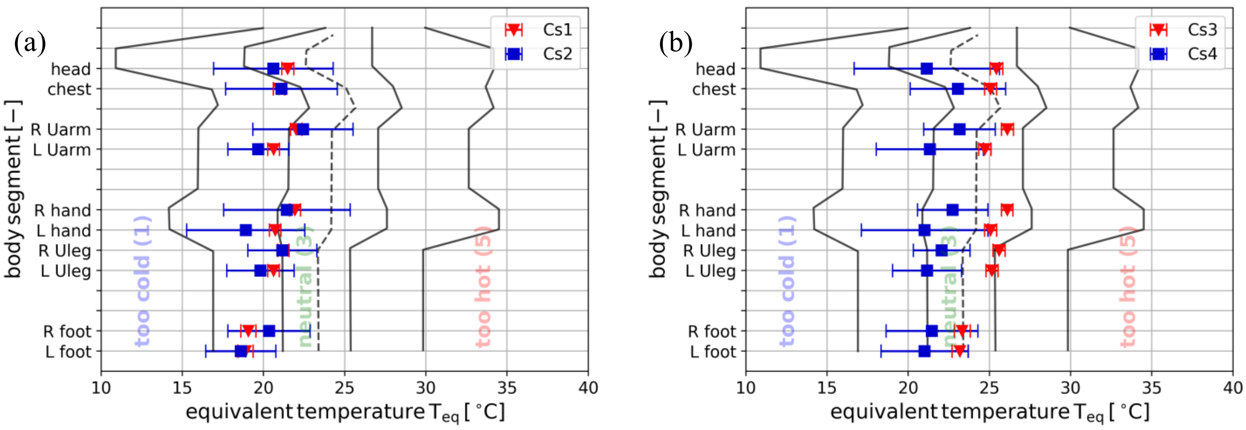

Figure 4. Results of the comparison of objective (triangles) and subjective (squares) thermal comfort ratings for MJV with T_{in}=15°C (a) and 19°C (b).

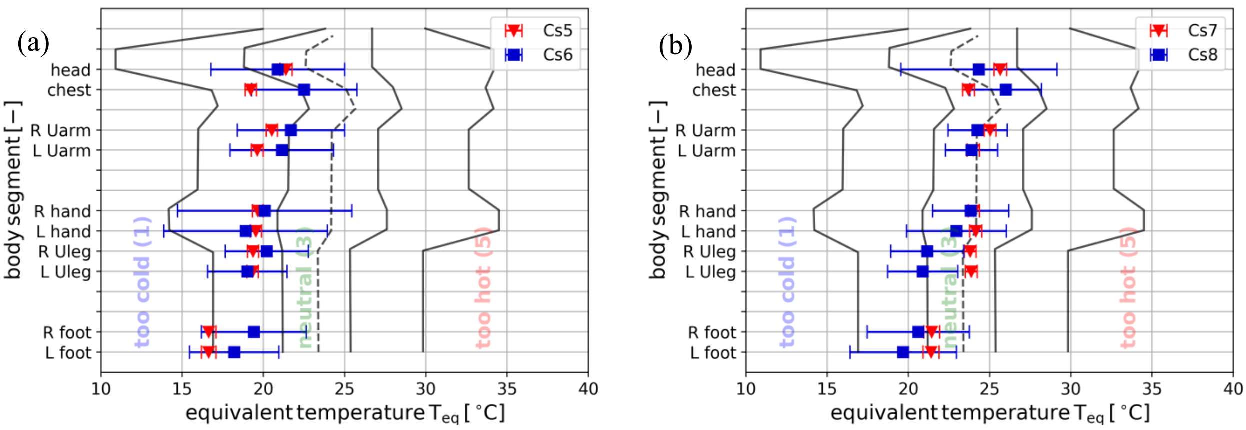

Figure 5. Results of the comparison of objective (triangles) and subjective (squares) thermal comfort ratings for DV with T_{in}=15°C (a) and 19°C (b).

Figure 4a) displays the results for MJV for an inflow air temperature of 15°C. The objective (Cs1) and subjective values (Cs2) show that this ventilation scenario provides slightly uncomfortable conditions. All considered body parts except for the head, the right upper arm (R Uarm) and the right hand (R hand) are rated comfortable but cold. The objective (Cs1) comfort assessment corresponds well with the subjective (Cs2) comfort evaluation for all investigated body parts. A maximum deviation of 1.8 K is found for the left hand, which might be caused by a different alignment of the subjects compared to the TM. The higher inflow temperatures (see figure 4b) provide neutral, comfortable thermal conditions evaluated using both methods of comfort assessment. However, the objectively measured T_{eq} values based on the TM (Cs3) are significantly higher compared to the calculated values based on the subject trials (Cs4) with a maximum deviation of 4.3K on head level. One reason for this result is that the subject test for this specific ventilation scenario was conducted in the second time slot of the schedule, see description of the methodology in section 3.1. Here, the subjects were in warmer conditions in the first phase. Accordingly they were exposed to a decrease of the temperature, which strongly influences the subjective perception of temperature and therefore also the thermal comfort rating.

In general, we observed slightly too cold temperatures for DV with an inflow temperature of 15°C (see figure 5a), especially for the lower body parts. The objective measurements reflected comfort-critical cold temperatures on foot level in contrast to the remaining body parts, where the evaluation was cold but comfortable. Hence, temperature stratification from head to foot level of almost 5 K occurred. The comparison between the data of the objective and subjective thermal comfort rating showed good agreement within the error range. However, at chest level a maximum deviation of 3.3 K occurred. The data for DV with T_{in}=19°C are depicted in figure 5b. Here, the temperatures of the upper body were assessed as neutrally comfortable, whereas the lower body parts showed significantly colder, but still comfortable temperatures. Generally, the values of the objective (Cs7) and subjective (Cs8) comfort assessment correlated quite well within the error ranges. However, for the upper legs and the chest, the subjective determined data differed from the objective measured values by a maximum deviation of 3 K.

5. Conclusion

Using subject tests and the experimental acquisition of local equivalent temperatures, global thermal passenger comfort was analysed in a generic train compartment for two different ventilation concepts and two different temperatures of the inflowing air (T_{in}=15°C and 19°C). The studied ventilation concepts comprised a simplified state-of-the-art micro-jet ventilation as well as a displacement ventilation concept. A calibrated TM was used to determine thermal comfort parameters based on body-part related equivalent temperatures. In order to compare both methods of thermal comfort ratings, the results of the temperature sensation (not including local discomfort ratings, e.g. temperature stratification or draught rate) assessed during subject tests were translated into equivalent temperatures. For steady-state thermal conditions within the compartment, a good agreement between subjectively and objectively captured data has been obtained. Here, local values of the corresponding body parts differed by less than 3.3 K and were usually within the error bars of each other. However, especially the calculated data based on subject tests were governed by a larger variation, which is a result of the fact that the sensation of temperatures, i.e. thermal comfort, is subject to additional individual influences. Nonetheless, the local equivalent temperatures reflected both spatial differences regarding the thermal comfort of single body parts as well as the changed thermal sensation for different temperatures of the inflowing air and different ventilation concepts. Accordingly, the equivalent temperature can be regarded as a suitable index of thermal comfort if subject tests are not available. The holistic evaluation of the ventilation systems regarding thermal comfort leads to the conclusion that none of the concepts provide overall neutral comfortable conditions for colder inflow air temperatures. In contrast, high air-supply temperatures lead to neutral comfortable conditions.

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References

[1] European Commission: White Paper on transport – roadmap to a single European transport area – Towards a competitive resource-efficient transport system. 2011. Publications Office of the European Union, Luxembourg. ISBN: 978-92-79-18270-9. doi: 10.2832/30955
[2] ASHRAE Handbook Fundamentals – Chapter 8: Thermal Comfort 2001 American Society of Heating, Refrigeration and Air-Conditioning Engineers, Inc.
[3] Mayer E and Schwab R 2004. Eur J Appl Physiol **92**: 626-629
[4] Lange P, Westhoff A, Schmeling D and Bosbach J 2018, Cost-effective human comfort with realistic thermal load for studies of convection-driven ventilation systems, Roomvent & Ventilation Conference, Espoo, Finland ISBN: 978-952-5236-48-4, pages 367-372
[5] SAE: Equivalent temperature 1993 SAE Surface Vehicle Information Report. J2234
[6] Schmeling D and Bosbach J 2017. Build. Environ **125** 248-260
[7] EN 13129 2016 Railway Applications – Air conditioning for mainline rolling stock – Comfort parameters and type tests.
[8] Hörmann H J, Maier J and Zierke O 2017, Passenger's assessment of thermal comfort in a railway car-mock-up with displacement ventilation, European Transport Conference, Barcelona, Spain
[9] EN 14505-2 2006 Ergonomics of the thermal environment – Evaluation of thermal environments in vehicles – Part 2: Determination of equivalent temperature